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# Low Toxic Corrosion Inhibitors for Aluminum in Fresh Water

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# Low Toxic Corrosion Inhibitors for Aluminum in Fresh Water

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**Scientific and Technical
Information Office**

1978

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TECHNICAL PAPER

# LOW TOXIC CORROSION INHIBITORS FOR ALUMINUM IN FRESH WATER

## INTRODUCTION

Water is considered an extremely corrosive medium because it is the best known universal solvent and often contains corrosive salts. Some method is normally required to reduce the attack on most metals by water, and additions of corrosion inhibitors are widely used because of simplicity and economics. A few commonly used inorganic inhibitors are chromates, borates, nitrates, nitrites, phosphates, and silicates.

The most effective chemicals for inhibiting the action of fresh water on aluminum and steel are chromates, which have been widely used for many years. Recent government restrictions on the use and disposal of chromates and other toxic materials have generated a need for low toxic inhibitors. This is paramount when large quantities of water are involved as in proof testing large pressure vessels. Previous laboratory tests and service experience have indicated that single chemicals other than chromates are only partially effective in reducing the action of corrosive waters on aluminum. This investigation was made to evaluate the effectiveness of combinations of chemical compounds as corrosion inhibitors.

## TEST PROCEDURE

Several inorganic chemicals (borate, nitrate, nitrite, phosphate, silicate) that had shown promise as corrosion inhibitors for aluminum were selected for this investigation. Combinations of these chemicals were tested because invidually they were only partially effective corrosion inhibitors. Sodium mercaptobenzothiazole (NaMBT) was included because of its effectiveness in systems involving copper or copper ions.

A prerequisite for evaluating inhibitors is availability of a corrosive test medium. A suitable medium was formulated and consisted of distilled water containing 138 ppm (parts per million) sodium bicarbonate, 148 ppm sodium sulfate, and 165 ppm sodium chloride (100 ppm each of bicarbonate, sulfate and chloride ions) with and without 0.2 ppm copper sulfate. The copper sulfate was added to simulate water contaminated with copper either from copper ions in the source water or from copper components in the system. Initially the inhibitors were tested in corrosive water and corrosive water containing copper sulfate. The use of corrosive water without copper was eventually discontinued because the corrosive water containing copper was a more severe test medium and there is always the possibility of water being contaminated with copper ions. Fifty inhibitors consisting of various combinations and concentrations of sodium borate, nitrate, nitrite, phosphate, silicate, and mecaptobenzothiazole (MBT) were tested (Table 1). Sodium chromate was included in the test program as a standard for comparison.

Specimens, 2.5 by 10 cm, were sheared from 0.16 cm thick sheet of 2219-T87 aluminum. This alloy was chosen because it is used extensively in the construction of large tanks, notably the Space Shuttle external propellant tank, and is a weldable high strength alloy with low corrosion resistance. The specimens were deburred, degreased in acetone, and weighed. They were partially (approximately one-half) immersed in 300 ml of solution contained in 500 ml covered bottles, and stored at room temperature. In general, specimens were removed after 6 months unless they had suffered significant corrosion after 1 month at which time they were removed. A few tests involved extremely high inhibitor concentrations, on the order of 5 to 10 grams/liter. Exposure time in these tests was 14 months. After exposure, the specimens were cleaned in 70 percent nitric acid, weighed, and visually examined for type and distribution of corrosion.

## RESULTS AND DISCUSSION

Because perforation will make most water systems inoperative, the type and depth of attack instead of weight loss were the major factors used to evaluate the test specimens and to rate the inhibitors. Weight loss, which is an effective criterion mainly for uniform corrosion, was used in rating specimens with similar corrosion patterns and for specimens where the pitting frequency or area affected by nonuniform attack was approximately the same. Although the

test data for the inhibitors in corrosive water without copper are listed in Table 2 (Water "A"), the inhibitors were rated mainly on their performance in the water containing copper ions (Water "B"). The inhibitors were placed in four categories based on the degree of corrosion protection they provided. The first category which contained eight inhibitors was rated excellent. The specimens showed no visible signs of corrosion, and the weight loss was less than 2 mg. These inhibitors were as effective as sodium chromate. Thirteen inhibitors were placed in the second category and rated good. The specimens had not suffered any significant localized attack, and the weight loss was less than 10 mg. The remaining inhibitors were rated fair and poor. The appearance of the test specimens after exposure is shown in Figure 1.

Considering only the test inhibitors at low concentrations (1.0 gram/liter or less) it appears that nitrate, phosphate, silicate and, in most cases, MBT were necessary for an effective inhibitor. Also a concentration of 1 gram/liter (1000 ppm) of total chemical constituents was necessary, whereas 0.1 gram/liter (100 ppm) sodium chromate was sufficient. It is always a good policy to use some excess inhibitor as a buffer against depletion unless frequent monitoring is employed.

All the inhibited solutions were alkaline and in general the pH of the most effective inhibitors was greater than 9.5. This is surprising since solutions that are moderately to highly alkaline (pH 9 or higher) are normally corrosive to aluminum. Tests were conducted to determine the effect of reducing the pH of some of the most effective inhibitors. Trisodium phosphate was used in all of the original inhibitors because phosphate is a good buffer and inhibitor. The method chosen to reduce the pH of the inhibitors was to substitute monosodium phosphate and phosphoric acid for trisodium phosphate and still maintain approximately the same phosphate concentration. Another method employed was to substitute hydrochloric acid for the sodium chloride in the corrosive water. As may be noted in Table 3, the inhibitors containing trisodium phosphate were significantly superior in performance to the others. Although there were some variations, in general there was little difference in the performance of the inhibitors containing the other three chemicals (monosodium phosphate, phosphoric acid, and hydrochloric acid).

Several inhibitors were evaluated at relatively high concentrations, 5 and 10 grams/liter, and were exposed for 14 months instead of 6 months. None of the inhibitors contained NaMBT and only corrosive water without copper sulfate was used. The performance of all nine of these inhibitors was very good

(Table 2) and compared favorably with sodium chromate. As opposed to the low concentration inhibitors, neither MBT nor silicate were required for effective performance. However, it should be recalled that these tests were conducted in a corrosive water with no copper sulfate added.

## CONCLUSIONS

As indicated in Table 2, 8 of a total of 50 test compounds were effective in inhibiting the attack of corrosive water on 2219 aluminum and compared very favorably with sodium chromate. The advantage of these eight compounds over sodium chromate is that they are not considered toxic and are therefore safe and easily disposable. The disadvantages are that the compounds are composed of four to six different chemicals and the total concentration required ranges from 0.5 to 1.0 gram/liter (500 to 1000 ppm) whereas only 0.1 to 0.2 gram/liter (100 to 200 ppm) of sodium chromate is required for effective inhibition. An additional 13 compounds gave very good protection, but some minor corrosion was encountered. None of the remaining test compounds should be considered effective inhibitors. It should be noted that the results are based on a 6-month test. Under conditions of extended service (greater than 6 months) and non-monitoring of the concentration, considerat on should be given to increasing the original dosage or adding additional inhibito: periodically to make allowances for possible depletion.

Reducing the alkalinity of the inhibitors by substituting monosodium phosphate or phosphoric acid for trisodium phosphate or replacing the sodium chloride in the corrosive water with hydrochloric acid was not an effective method of improving performance. In most cases the compounds containing trisodium phosphate and having the highest pH were the most effective.

All nine compounds that were evaluated at high concentrations (5 to 10 grams/liter) were very effective corrosion inhibitors in water containing no copper ions and compared favorably with sodium chromate. From an economic standpoint, the inhibitors that are effective at a lower concentration are preferred.

Figure 1. Appearance of 2219-87 test specimens.

TABLE 1. COMPOSITION OF TEST INHIBITORS

Concentration in Decigrams per Liter

| | |
|---|---|
| 1. | 2 $Na_3PO_4 \cdot 12H_2C$, 3 $Na_2SiO_3 \cdot 9H_2O$ |
| 2a. | 1.5 $NaNO_3$, 1.5 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2SiO_3 \cdot 9H_2O$ |
| 2b. | 3 $NaNO_3$, 3 $Na_3PO_4 \cdot 12H_2O$, 4 $Na_2SiO_3 \cdot 9H_2O$ |
| 2c. | 15 $NaNO_3$, 15 $Na_3PO_4 \cdot 12H_2O$, 20 $Na_2SiO_3 \cdot 9H_2O$ |
| 2d. | 30 $NaNO_3$, 30 $Na_3PO_4 \cdot 12H_2O$, 40 $Na_2SiO_3 \cdot 9H_2O$ |
| 3a. | 1 $NaNO_3$, 1 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2SiO_3 \cdot 9H_2O$ |
| 3b. | 2 $NaNO_3$, 2 $NaNO_2$, 2 $Na_3PO_4 \cdot 12H_2O$, 4 $Na_2SiO_3 \cdot 9H_2O$ |
| 3c. | 20 $NaNO_3$, 20 $NaNO_2$, 20 $Na_3PO_4 \cdot 12H_2O$, 40 $Na_2SiO_3 \cdot 9H_2O$ |
| 4. | 2 $NaNO_3$, 2 $NaNO_2$, 1 $NaH_2PO_4 \cdot H_2O$, 4 $Na_2SiO_3 \cdot 9H_2O$ |
| 5. | 2 $NaNO_3$, 2 $NaNO_2$, 0.5 $H_3PO_4$, 4 $Na_2SiO_3 \cdot 9H_2O$ |
| 6. | 8 $Na_2SiO_3 \cdot 9H_2O$, 4 NaMBT |
| 7a. | 1 $Na_3PO_4 \cdot 12H_2O$, 3 $Na_2SiO_3 \cdot 9H_2O$, 1 NaMBT |
| 7b. | 1.5 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2SiO_3 \cdot 9H_2O$, 1.5 NaMBT |
| 7c. | 2 $Na_3PO_4 \cdot 12H_2O$, 5 $Na_2SiO_3 \cdot 9H_2O$, 4 NaMBT |
| 8. | 1 $NaH_2PO_4 \cdot H_2O$, 5 $Na_2SiO_3 \cdot 9H_2O$, 4 NaMBT |
| 9. | 0.5 $H_3PO_4$, 5 $Na_2SiO_3 \cdot 9H_2O$, 4 NaMBT |
| 10a. | 1 $NaNO_3$, 1 $Na_3PO_4 \cdot 12H_2O$, 1.5 $Na_2SiO_3 \cdot 9H_2O$, 1.5 NaMBT |
| 10b. | 1 $NaNO_3$, 1 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2SiO_3 \cdot 9H_2O$, 1 NaMBT |
| 10c. | 2 $NaNO_3$, 2 $Na_3PO_4 \cdot 12H_2O$, 3 $Na_2SiO_3 \cdot 9H_2O$, 3 NaMBT |
| 11. | 2 $NaNO_3$, 1 $NaH_2PO_4 \cdot H_2O$, 3 $Na_2SiO_3 \cdot 9H_2O$, 3 NaMBT |
| 12. | 2 $NaNO_3$, 0.5 $H_3PO_4$, 3 $Na_2SiO_3 \cdot 9H_2O$, 3 NaMBT |
| 13a. | 1 $NaNO_3$, 1 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 1 $Na_2SiO_3 \cdot 9H_2O$, 1.5 NaMBT |

TABLE 1. (Continued)

13b. 1 $NaNO_3$, 0.5 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 1.5 $Na_2SiO_3 \cdot 9H_2O$, 1 NaMBT

13c. 2 $NaNO_3$, 1 $NaNO_2$, 2 $Na_3PO_4 \cdot 12H_2O$, 3 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

14. 2 $NaNO_3$, 1 $NaNO_2$, 1 $NaH_2PO_4 \cdot H_2O$, 3 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

15. 2 $NaNO_3$, 1 $NaNO_2$, 0.5 $H_3PO_4$, 3 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

16a. 1.5 $NaNO_3$, 1.5 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2B_4O_7$

16b. 3 $NaNO_3$, 3 $Na_3PO_4 \cdot 12H_2O$, 4 $Na_2B_4O_7$

16c. 15 $NaNO_3$, 15 $Na_3PO_4 \cdot 12H_2O$, 20 $Na_2B_4O_7$

16d. 30 $NaNO_3$, 30 $Na_3PO_4 \cdot 12H_2O$, 40 $Na_2B_4O_7$

17a. 1 $NaNO_3$, 1 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2B_4O_7$

17b. 2 $NaNO_3$, 2 $NaNO_2$, 2 $Na_3PO_4 \cdot 12H_2O$, 4 $Na_2B_4O_7$

17c. 20 $NaNO_3$, 20 $NaNO_2$, 20 $Na_3PO_4 \cdot 12H_2O$, 40 $Na_2B_4O_7$

18. 1 $NaNO_3$, 1 $Na_3PO_4 \cdot 12H_2O$, 1.5 $Na_2B_4O_7$, 1.5 NaMBT

19. 1 $NaNO_3$, 1 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 1 $Na_2B_4O_7$, 1.5 NaMBT

20a. 1 $NaNO_3$, 1 $Na_3PO_4 \cdot 12H_2O$, 1.5 $Na_2B_4O_7$, 1.5 $Na_2SiO_3 \cdot 9H_2O$

20b. 2 $NaNO_3$, 2 $Na_3PO_4 \cdot 12H_2O$, 3 $Na_2B_4O_7$, 3 $Na_2SiO_3 \cdot 9H_2O$

20c. 10 $NaNO_3$, 10 $Na_3PO_4 \cdot 12H_2O$, 20 $Na_2B_4O_7$, 10 $Na_2SiO_3 \cdot 9H_2O$

20d. 20 $NaNO_3$, 20 $Na_3PO_4 \cdot 12H_2O$, 40 $Na_2B_4O_7$, 20 $Na_2SiO_3 \cdot 9H_2O$

21a. 1 $NaNO_3$, 1 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 1 $Na_2B_4O_7$, 1 $Na_2SiO_3 \cdot 9H_2O$

21b. 2 $NaNO_3$, 2 $NaNO_2$, 2 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2B_4O_7$, 2 $Na_2SiO_3 \cdot 9H_2O$

21c. 20 $NaNO_3$, 20 $NaNO_2$, 20 $Na_3PO_4 \cdot 12H_2O$, 20 $Na_2B_4O_7$, 20 $Na_2SiO_3 \cdot 9H_2O$

22a. 1 $Na_2B_4O_7$, 3 $Na_2SiO_3 \cdot 9H_2O$, 1 NaMBT

22b. 1.5 $Na_2B_4O_7$, 2 $Na_2SiO_3 \cdot 9H_2O$, 1.5 NaMBT

22c. 3 $Na_2B_4O_7$, 4 $Na_2SiO_3 \cdot 9H_2O$, 3 NaMBT

23a. 1 $NaNO_3$, 1 $Na_3PO_4 \cdot 12H_2O$, 1 $Na_2B_4O_7$, 1 $Na_2SiO_3 \cdot 9H_2O$, 1 NaMBT

TABLE 1. (Concluded)

23b. 1 $NaNO_3$, 1 $Na_3PO_4 \cdot 12H_2O$, 1 $Na_2B_4O_7$, 1 $Na_2SiO_3 \cdot 9H_2O$, 1.5 NaMBT

23c. 2 $NaNO_3$, 2 $Na_3PO_4 \cdot 12H_2O$, 2 $Na_2B_4O_7$, 2 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

24. 2 $NaNO_3$, 1 $NaH_2PO_4 \cdot H_2O$, 2 $Na_2B_4O_7$, 2 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

25. 2 $NaNO_3$, 0.5 $H_3PO_4$, 2 $Na_2B_4O_7$, 2 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

26a. 0.5 $NaNO_3$, 0.5 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 1 $Na_2B_4O_7$, 1 $Na_2SiO_3 \cdot 9H_2O$, 1.5 NaMBT

26b. 1 $NaNO_3$, 0.5 $NaNO_2$, 1 $Na_3PO_4 \cdot 12H_2O$, 0.5 $Na_2B_4O_7$, 1 $Na_2SiO_3 \cdot 9H_2O$, 1 NaMBT

26c. 2 $NaNO_3$, 1 $NaNO_2$, 2 $Na_3PO_4 \cdot 12H_2O$, 1 $Na_2B_4O_7$, 2 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

27. 2 $NaNO_3$, 1 $NaNO_2$, 1 $NaH_2PO_4 \cdot H_2O$, 1 $Na_2B_4O_7$, 2 $Na_2SiO_3 \cdot 9H_2O$, 2 NaMBT

28a-d. 1, 2, 5, 10 $Na_2CrO_4$

$Na_2B_4O_7$ – sodium borate

$Na_2CrO_4$ – sodium chromate

$NaNO_2$ – sodium nitrite

$NaNO_3$ – sodium nitrate

$NaH_2PO_4 \cdot H_2O$ – monosodium phosphate

$Na_3PO_4 \cdot 12H_2O$ – trisodium phosphate

$H_3PO_4$ – phosphoric acid

$Na_2SiO_3 \cdot 9H_2O$ – sodium silicate

NaMBT – sodium mercaptobenzothiazole (50% solution)

## TABLE 2. RATINGS OF INHIBITORS AS TO EFFECTIVENESS

| Inhibitor No. | Inhibitor (decigrams/liter) | pH | Water Type | Time (mo) | Wt. Loss (mg) | Type of Attack |
|---|---|---|---|---|---|---|
| | **EXCELLENT**[2] | | | | | |
| 3b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 4 $SiO_3$ | 10.0 | B | 6 | 1.4 | U |
| 3b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 4 $SiO_3$ | 10.0 | A | 6 | 1.0 | U |
| 10a. | 1 $NO_3$, 1 $PO_4$, 1.5 $SiO_3$, 1.5 MBT | 9.8 | B | 6 | 1.0 | U |
| 10c. | 2 $NO_3$, 2 $PO_4$, 3 $SiO_3$, 3 MBT | 10.1 | B | 6 | 1.0 | U |
| 13c. | 2 $NO_3$, 1 $NO_2$, 2 $PO_4$, 3 $SiO_3$, 2 MBT | 10.1 | B | 6 | 1.3 | U |
| 15. | 2 $NO_3$, 1 $NO_2$, 0.5 $H_3PO_4$, 3 $SiO_3$, 2 MBT | 8.4 | B | 6 | 1.3 | U |
| 23c. | 2 $NO_3$, 2 $PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 9.6 | B | 6 | 1.0 | U |
| 26c. | 2 $NO_3$, 1 $NO_2$, 2 $PO_4$, 1 $B_4O_7$, 2 $SiO_3$, 2 MBT | 9.6 | B | 6 | 1.0 | U |
| 27. | 2 $NO_3$, 1 $NO_2$, 1 $H_2PO_4$, 1 $B_4O_7$, 2 $SiO_3$, 2 MBT | 8.5 | B | 6 | 1.5 | U |
| 28a-d. | 1, 2, 5, 10 $CrO_4$ | 8.6 | B | 6 | 1.4-3.4 | U |
| | **GOOD**[2] | | | | | |
| 2b. | 3 $NO_3$, 3 $PO_4$, 4 $SiO_3$ | 10.0 | B | 6 | 6.7 | N(v) |
| 2b. | 3 $NO_3$, 3 $PO_4$, 4 $SiO_3$ | 10.0 | A | 6 | 1.0 | U |
| 6. | 6 $SiO_3$, 4 MBT | 9.6 | B | 6 | 6.2 | N(ll, v) |
| 7c. | 2 $PO_4$, 5 $SiO_3$, 4 MBT | 10.3 | B | 6 | 3.6 | N(l, v) |
| 8. | 1 $H_2PO_4$, 5 $SiO_3$, 4 MBT | 9.5 | B | 6 | 4.9 | N(v) |
| 9. | 0.5 $H_3PO_4$, 5 $SiO_3$, 4 MBT | 9.3 | B | 6 | 9.9 | N(v) |
| 10b. | 1 $NO_3$, 1 $PO_4$, 2 $SiO_3$, 1 MBT | 9.8 | B | 6 | 1.3 | N(v) |
| 13b. | 1 $NO_3$, 0.5 $NO_2$, 1 $PO_4$, 1.5 $SiO_3$, 1 MBT | 9.7 | B | 6 | 6.0 | N(ll, v) |
| 20b. | 2 $NO_3$, 2 $PO_4$, 3 $B_4O_7$, 3 $SiO_3$ | 9.6 | B | 6 | 9.3 | N(l) |
| 20b. | 2 $NO_3$, 2 $PO_4$, 3 $B_4O_7$, 3 $SiO_3$ | 9.6 | A | 6 | 1.0 | U |
| 21b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 2 $B_4O_7$, 2 $SiO_3$ | 9.6 | B | 6 | 4.9 | N(v) |
| 21b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 2 $B_4O_7$, 2 $SiO_3$ | 9.6 | A | 6 | 1.4 | U |
| 22a. | 1 $B_4O_7$, 3 $SiO_3$, 1 MBT | 8.7 | B | 6 | 1.0 | P(l) |
| 22b. | 1.5 $B_4O_7$, 5 $SiO_3$, 4 MBT | 9.5 | B | 6 | 4.9 | N(v) |
| 22c. | 3 $B_4O_7$, 4 $SiO_3$, 3 MBT | 8.7 | B | 6 | 9.4 | N(v) |
| 24. | 2 $NO_3$, 1 $H_2PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 8.5 | B | 6 | 9.3 | N(v) |
| | **FAIR**[2] | | | | | |
| 4. | 2 $NO_3$, 2 $NO_2$, 1 $H_2PO_4$, 4 $SiO_3$ | 10.0 | B | 6 | 19.9 | P(ll) |
| 7a. | 1 $PO_4$, 3 $SiO_3$, 1 MBT | 10.2 | B | 6 | 1.0 | P(l) |
| 7a. | 1 $PO_4$, 3 $SiO_3$, 1 MBT | 10.2 | A | 6 | 1.0 | N(v) |
| 7b. | 1.5 $PO_4$, 2 $SiO_3$, 1.5 MBT | 10.1 | B | 6 | 1.0 | P(l) |
| 7c. | 2 $PO_4$, 5 $SiO_3$, 4 MBT | 10.0 | C | 6 | 18.5 | E(ll, v) |
| 12. | 2 $NO_3$, 0.5 $H_3PO_4$, 3 $SiO_3$, 3 MBT | 8.2 | B | 6 | 11.7 | E(v) |
| 14. | 2 $NO_3$, 1 $NO_2$, 1 $H_2PO_4$, 3 $SiO_3$, 2 MBT | 10.0 | B | 6 | 17.6 | E(v) |
| 23c. | 2 $NO_3$, 2 $PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 7.0 | C | 6 | 15.8 | E(ll, v) |

TABLE 2. (Continued)

| Inhibitor No. | Inhibitor (decigrams/liter) | pH | Water Type | Time (mo) | Wt. Loss (mg) | Type of Attack |
|---|---|---|---|---|---|---|
| | POOR[3] | | | | | |
| 1. | 2 $PO_4$, 3 $SiO_3$ | 9.6 | B | 1 | 53.8 | P(l) |
| 1. | 2 $PO_4$, 3 $SiO_3$ | 9.6 | A | 1 | 31.8 | P(l) |
| 2a. | 1.5 $NO_3$, 1.5 $PO_4$, 2 $SiO_3$ | 9.7 | B | 1 | 47.0 | E,P(ll) |
| 2a. | 1.5 $NO_3$, 1.5 $PO_4$, 2 $SiO_3$ | 9.7 | A | 1 | 15.1 | P(ll) |
| 3a. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 2 $SiO_3$ | 10.0 | B | 1 | 19.5 | E, P(ll) |
| 3a. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 2 $SiO_3$ | 10.0 | A | 1 | 6.5 | P(ll) |
| 3b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 4 $SiO_3$ | 7.7 | C | 6 | 652.3 | P(ll, v) |
| 5. | 2 $NO_3$, 2 $NO_2$, 0.5 $H_3PO_4$, 4 $SiO_3$ | 9.1 | B | 6 | 645.8 | P(sc) |
| 10c. | 2 $NO_3$, 2 $PO_4$, 3 $SiO_3$, 3 MBT | 7.0 | C | 6 | 40.6 | E(v) |
| 11. | 2 $NO_3$, 1 $H_2PO_4$, 3 $SiO_3$, 3 MBT | 9.0 | B | 6 | 47.0 | P(v) |
| 13a. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 1 $SiO_3$, 1.5 MBT | 9.7 | B | 1 | 12.9 | P(ll) |
| 13c. | 2 $NO_3$, 1 $NO_2$, 2 $PO_4$, 3 $SiO_3$, 2 MBT | 17.1 | C | 6 | 110.7 | N(v) |
| 16a. | 1.5 $NO_3$, 1.5 $PO_4$, 2 $B_4O_7$ | 9.1 | B | 1 | 42.3 | E, P(ll) |
| 16a. | 1.5 $NO_3$, 1.5 $PO_4$, 2 $B_4O_7$ | 9.1 | A | 1 | 28.8 | P(ll) |
| 16b. | 3 $NO_3$, 3 $PO_4$, 4 $B_4O_7$ | 9.3 | B | 1 | 70.9 | E, P(ll) |
| 16b. | 3 $NO_3$, 3 $PO_4$, 4 $B_4O_7$ | 9.3 | A | 1 | 52.6 | E, P(l) |
| 17a. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 2 $B_4O_7$ | 9.3 | B | 1 | 75.1 | P(ll) |
| 17a. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 2 $B_4O_7$ | 9.3 | A | 1 | 72.6 | P(ll) |
| 17b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 4 $B_4O_7$ | 9.3 | B | 1 | 53.2 | E, P(ll) |
| 17b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 4 $B_4O_7$ | 9.3 | A | 1 | 60.4 | E, P(ll) |
| 18. | 1 $NO_3$, 1 $PO_4$, 1.5 $B_4O_7$, 1.5 MBT | 9.2 | B | 1 | 52.0 | N(sc) |
| 19. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 1 $B_4O_7$, 1.5 MBT | 9.2 | B | 1 | 47.5 | N(sc) |
| 20a. | 1 $NO_3$, 1 $PO_4$, 1.5 $B_4O_7$, 1.5 $SiO_3$ | 9.3 | B | 1 | 12.5 | P(l) |
| 20a. | 1 $NO_3$, 1 $PO_4$, 1.5 $B_4O_7$, 1.5 $SiO_3$ | 9.3 | A | 1 | 5.5 | P(l) |
| 21a. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 1 $B_4O_7$, 1 $SiO_3$ | 9.4 | B | 1 | 36.4 | E, P(ll) |
| 21a. | 1 $NO_3$, 1 $NO_2$, 1 $PO_4$, 1 $B_4O_7$, 1 $SiO_3$ | 9.4 | A | 1 | 3.8 | N(l) |
| 23a. | 1 $NO_3$, 1 $PO_4$, 1 $B_4O_7$, 1 $SiO_3$, 1 MBT | 9.6 | B | 1 | 15.7 | N(v) |
| 23b. | 1 $NO_3$, 1 $PO_4$, 1 $B_4O_7$, 1 $SiO_3$, 1.5 MBT | 9.6 | B | 1 | 5.4 | N(l) |
| 25. | 2 $NO_3$, 0.5 $H_3PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 8.4 | B | 6 | 32.1 | P(ll) |
| 26a. | 0.5 $NO_3$, 0.5 $NO_2$, 1 $PO_4$, 1 $B_4O_7$, 1 $SiO_3$, 1.5 MBT | 9.6 | B | 1 | 10.8 | N(l) |
| 26b. | 1 $NO_3$, 0.5 $NO_2$, 1 $PO_4$, 0.5 $B_4O_7$, 1 $SiO_3$, 1 MBT | 9.6 | B | 2 | 3.4 | N(l) |
| 29. | None (2 tests) | 8.5 | A | 6 | 126-136 | P(sc) |
| 29. | None (4 tests) | 8.5 | B | 6 | 127-136 | P(sc) |

## TABLE 2. (Concluded)

| Inhibitor No. | Inhibitor (decigrams/liter) | pH | Water Type | Time (mo) | Wt. Loss (mg) | Type of Attack |
|---|---|---|---|---|---|---|
| | HIGH CONCENTRATIONS[2] | | | | | |
| 2c. | 15 $NO_3$ 15 $PO_4$, 20 $SiO_3$ | 11.3 | A | 14 | 21.7 | E |
| 2d. | 30 $NO_3$, 30 $PO_4$, 40 $SiO_3$ | 11.4 | A | 14 | 24.6 | E |
| 3c. | 20 $NO_3$, 20 $NO_2$, 20 $PO_4$, 40 $SiO_3$ | 11.4 | A | 14 | 15.9 | E |
| 16c. | 15 $NO_3$, 15 $PO_4$, 20 $B_4O_7$ | 9.3 | A | 14 | 30.4 | E |
| 16d. | 30 $NO_3$, 30 $PO_4$, 40 $B_4O_7$ | 9.3 | A | 14 | 17.5 | E |
| 17c. | 20 $NO_3$, 20 $NO_2$, 20 $PO_4$, 40 $B_4O_7$ | 9.4 | A | 14 | 15.9 | E |
| 20c. | 10 $NO_3$, 10 $PO_4$, 20 $B_4O_7$, 10 $SiO_3$ | 9.6 | A | 14 | 27.1 | E |
| 20d. | 20 $NO_3$, 20 $PO_4$, 40 $B_4O_7$, 20 $SiO_3$ | 9.6 | A | 14 | 23.1 | E |
| 21c. | 20 $NO_3$, 20 $NO_2$, 20 $PO_4$, 20 $B_4O_7$, 20 $SiO_3$ | 9.4 | A | 14 | 18.0 | E |
| 28d. | 10 $CrO_4$ | 8.6 | A | 14 | 17.5 | E |
| 29. | None | 8.0 | A | 14 | 197.0 | P(sc) |

A - Corrosive water
B - Corrosive water plus 0.2 ppm $CuSO_4$
C - Same as "B" except 100 ppm HCl substituted for 82 ppm NaCl for pH adjustment
E - Etched
l - Liquid
ll - Liquid level
N - Nonuniform corrosion
P - Pitted
sc - Scattered
U - No visible corrosion
v - Vapor

Note: (1) The chemical formulas are abbreviated for convenience. See Table 1 for complete formulas.
(2) The inhibitors are listed in numerical order and the difference in performance within each category is small.
(3) The inhibitors are listed in numerical order.

TABLE 3. EFFECT OF pH ON INHIBITOR PERFORMANCE

| Inhibitor No. | Inhibitor[1] (decigrams/liter) | pH | Rating[3] |
|---|---|---|---|
| | **Nitrate, Nitrite, Phosphate, Silicate** | | |
| 3b. | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 4 $SiO_3$ | 10.0 | E |
| 4. | 2 $NO_3$, 2 $NO_2$, 1 $H_2PO_4$, 4 $SiO_3$ | 10.0 | F |
| 5. | 2 $NO_3$, 2 $NO_2$, 0.5 $H_3PO_4$, 4 $SiO_3$ | 9.1 | P |
| 3b.[2] | 2 $NO_3$, 2 $NO_2$, 2 $PO_4$, 4 $SiO_3$ | 7.7 | P |
| | **Phosphate, Silicate, MBT** | | |
| 7c. | 2 $PO_4$, 5 $SiO_3$, 4 MBT | 10.3 | G |
| 8. | 1 $H_2PO_4$, 5 $SiO_3$, 4 MBT | 9.5 | F |
| 9. | 0.5 $H_3PO_4$, 5 $SiO_3$, 4 MBT | 9.3 | F |
| 7c.[2] | 2 $PO_4$, 5 $SiO_3$, 4 MBT | 9.0 | F |
| | **Nitrate, Phosphate, Silicate, MBT** | | |
| 10c. | 2 $NO_3$, 2 $PO_4$, 3 $SiO_3$, 3 MBT | 10.1 | E |
| 11. | 2 $NO_3$, 1 $H_2PO_4$, 3 $SiO_3$, 3 MBT | 9.0 | P |
| 12. | 2 $NO_3$, 0.5 $H_3PO_4$, 3 $SiO_3$, 3 MBT | 8.2 | F |
| 10c.[2] | 2 $NO_3$, 2 $PO_4$, 3 $SiO_3$, 3 MBT | 7.0 | P |
| | **Nitrate, Nitrite, Phosphate, Silicate, MBT** | | |
| 13c. | 2 $NO_3$, 1 $NO_2$, 2 $PO_4$, 3 $SiO_3$, 2 MBT | 10.1 | E |
| 14. | 2 $NO_3$, 1 $NO_2$, 1 $H_2PO_4$, 3 $SiO_3$, 2 MBT | 10.0 | F |
| 15. | 2 $NO_3$, 1 $NO_2$, 0.5 $H_3PO_4$, 3 $SiO_3$, 2 MBT | 8.4 | E |
| 13c.[2] | 2 $NO_3$, 1 $NO_2$, 2 $PO_4$, 3 $SiO_3$, 2 MBT | 7.1 | P |
| | **Nitrate, Phosphate, Borate, Silicate, MBT** | | |
| 23c. | 2 $NO_3$, 2 $PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 9.6 | E |
| 24. | 2 $NO_3$, 1 $H_2PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 8.5 | F |
| 25. | 2 $NO_3$, 0.5 $H_3PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 8.4 | G |
| 23c.[2] | 2 $NO_3$, 2 $PO_4$, 2 $B_4O_7$, 2 $SiO_3$, 2 MBT | 7.0 | F |
| | **Nitrate, Nitrite, Phosphate, Borate, Silicate, MBT** | | |
| 26c. | 2 $NO_3$, 1 $NO_2$, 2 $PO_4$, 1 $B_4O_7$, 2 $SiO_3$, 2 MBT | 9.6 | E |
| 27. | 2 $NO_3$, 1 $NO_2$, 1 $H_2PO_4$, 1 $B_4O_7$, 2 $SiO_3$, 2 MBT | 8.5 | E |

Note:

(1) The chemical formulas are abbreviated for convenience. See Table 1 for complete formulas.

(2) The pH of the solution was adjusted by substituting 100 ppm HCl for the NaCl in the corrosive water.

(3) E - excellent, G - good, F - fair, P - poor.

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16. ABSTRACT

Combinations of chemical compounds that reportedly reduce the corrosion of aluminum in fresh water were evaluated. These included combinations of borates, nitrates, nitrites, phosphates, silicates, and mercaptobenzothiazole. Eight of fifty inhibitor combinations evaluated gave excellent corrosion protection and compared favorably with sodium chromate, which has generally been considered standard for many years.

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